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An Overview of Health and Usage Monitoring Systems (HUMS) for Military Helicopters

K.F. Fraser

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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Airframes and Engines Division
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ABSTRACT

The application of HUMS for military helicopters is lagging that for civil helicopters, but military operators are seriously examining the effectiveness of such systems for their fleets. The material presented in this document is based mainly on the author's recent discussions with researchers, manufacturers and military operators. It outlines some of the important issues which operators face and some initiatives in the area.

Approved for public release

DEPARTMENT OF DEFENCE

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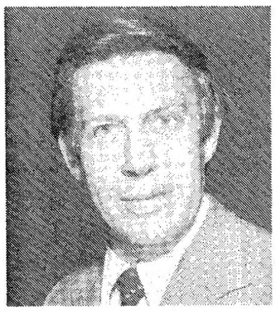

Mr Ken Fraser joined the Aeronautical Research Laboratory (as it was then known) in 1959 after graduating with honours from the University of Melbourne with a Bachelor of Electrical Engineering Degree. Since that time he has worked in various aeronautical fields including crash data recording, weapon kinematics, turbine engine health monitoring, turbine engine control and helicopter life assessment. He was involved in the development and flight demonstration of the world-first "black-box" aircraft crash data recorder which recorded cockpit voice and flight data on a magnetic wire medium. He developed a system for in-flight monitoring of the accumulated fatigue damage to heavily loaded helicopter gears; it was the first time a full fatigue damage calculation, which included component strength characteristics, had been performed during flight in a helicopter. Currently he is a Principal Research Scientist who manages helicopter fatigue life assessment work (structural and mechanical) undertaken by the laboratory on behalf of the Australian Defence Force. He pioneered the setting up , and is now a member, of an Australian Defence Organisation (including all three Services) Working Party which is providing guidance on the applicability of accident data recorders and HUMS (Health and Usage Monitoring Systems) to Australian Defence Force helicopters.

An Overview of Health and Usage Monitoring Systems (HUMS) for Military Helicopters

EXECUTIVE SUMMARY

1. The Report draws together insights gained from an examination of specialist views on the application of Health and Usage Monitoring Systems (HUMS) to military helicopters. These views were conveyed in discussions or correspondence with the author or in published works. Special attention is given to the views expressed by various manufacturers and military operators in the USA and the UK.

2. Multi-function systems now coming into service in some civil helicopters combine the functions of accident data recording and HUMS using common equipment. Similar systems are on order by some military operators and are being evaluated by others.

3. HUMS health monitoring technologies for the transmission and engine systems are fairly mature, and selected technologies are incorporated in current commercial HUMS. Rotor track and balance is also well handled in these HUMS but diagnosis of other rotor system faults has been identified as an area requiring much more research and development. The verification of health diagnostics and the development of a suitable means of interfacing with military aircraft maintainers continue to be health monitoring areas requiring much more attention.

4. HUMS usage monitoring has received far less attention than health monitoring. This appears to have occurred because the main emphasis to this time, for civil helicopters, has been on airworthiness aspects rather than cost benefits. Usage monitoring in currently available HUMS is limited to exceedance monitoring. Usage monitoring appears to be regarded as being more important for military than for civil operators, probably because there is a perception that, in general, military operations are more severe and more difficult to quantify than civil operations.

5. Military operators see great airworthiness benefit from health and usage monitoring techniques which provide warnings of impending failures and ensure that fatigue life-limited components are replaced before the risk of failure becomes unacceptable, but consider the fitting of HUMS can only be justified if quantifiable cost benefits can be demonstrated.

6. A major concern of military operators is that HUMS will become a large generator of data requiring an unacceptably high level of ground support. The development and implementation of improved information management strategies which address the specific requirements of the military environment are considered to be essential. The use of advanced information management methods, such as artificial intelligence techniques, is being actively pursued by some leading HUMS developers.

7. Research currently being undertaken on the synthesis of loads on rotating components from loads measured in the static system, may overcome some of the major concerns relating to the practicality of measuring important structural loads in the operational environment. The synthesis technique provides significant scope to place load sensors in benign locations and to minimise the number of sensors required. Developments in this area are likely to influence the technologies adopted for HUMS structural usage monitoring in the longer term.

8. A number of military working groups have been set up to investigate effectiveness or implementation issues for HUMS and accident data recorders.

9. Collaborative arrangements have been established under The Technical Cooperation Program, in the area of effectiveness of HUMS in the military environment.

CONTENTS

ABBREVIATIONS

AATD	Aviation Applied Technology Directorate (US Army)
ADF	Australian Defence Force
ADR	Accident Data Recorder
AI	Artificial Intelligence
ARA	Australian Regular Army
AMRL	Aeronautical and Maritime Research Laboratory (part of DSTO)
CAA	Civil Aviation Authority (UK)
CVR	Cockpit Voice Recorder
FLM	Flight Loads Monitoring (defined for use in this document)
DND	Department of National Defence (Canada)
DSTO	Defence Science and Technology Organisation (within ADF)
FCM	Flight Condition Monitoring (defined for use in this document)
EDMS	Engine Distress Monitoring System (SHL)
EEMS	Electrostatic Engine Monitoring System (Smiths Industries)
FDR	Flight Data Recorder
FDR/FA	Flight Data Recorder/Fault Analyser (for US Army helicopters)
GPAv	General Electric / Plessey Avionics
HHMAG	Helicopter Health Monitoring Advisory Group (set up by CAA)
HHUMIG	Tri-Service Helicopter HUM Implementation Group (for the UK)
HTP	(TTCP Sub Group) H Technical Panel
HUMS	Health and Usage Monitoring System(s)
IDMS	Ingested Debris Monitoring System (SHL)
LCF	Low cycle fatigue
MDHC	McDonnell Douglas Helicopter Company
MJAD	M.J. Andrew Dynamics (a UK company)
MOD	Ministry of Defence (UK)
MOD-PE	Ministry of Defence - Procurement Executive
MRGB	Main Rotor Gear Box
NAML	Naval Aircraft Materials Laboratory
NAWC	Naval Air Warfare Center (Trenton)
PLT	Parts Life Tracking
QDM	Quantitative Debris Monitor
R&D	Research and Development
RAAF	Royal Australian Air Force
RAN	Royal Australian Navy
RN	Royal Navy
RNLAF	Royal Netherlands Air Force
SDRS	Structural Data Recording Set (manuf. by Systems Electronics Inc.)
SHL	Stewart Hughes Limited
TII	Technology Integration Incorporated
TTCP	The Technical Control Panel
UK	United Kingdom
UMWG	Usage Monitoring Working Group (set up by HHMAG)
US	United States *(of America)*
USA	United States of America
USD	United States Dollar
WHL	Westland Helicopters Limited

1. INTRODUCTION

Permanently installed multi-function health and usage monitoring systems (HUMS) are being used increasingly by operators of civil helicopters to reduce maintenance costs and to improve the management of structural and mechanical integrity. The same unit that contains the HUMS is also being used to record selected data for incident and accident investigation purposes. The use of such systems in military helicopters is lagging that for civil helicopters but most military operators are actively considering the applicability of such systems to their helicopter fleets.

HUMS is an acronym used throughout the helicopter industry to cover a range of airworthiness and maintenance-related monitoring functions. In the context of HUMS, health monitoring refers to those functions which seek to signal the need for maintenance action if the monitored data do not lie within a "normal" or "healthy" range. Health monitoring is meant to include such functions as:

- Engine performance and diagnostics.
- Transmission early failure detection via vibration analysis or oil debris monitoring.
- Rotor smoothing and rotor diagnostics.

In the context of HUMS, usage monitoring refers to those functions which seek to provide an indication or take account of loading severity which could have an impact on the safe lives of fatigue life-limited components. Usage monitoring is meant to include:

- Exceedance monitoring.
- Flight condition (or regime) monitoring (including automatic gross weight estimation).
- Loads monitoring.
- Life expenditure monitoring.

It is to be emphasised that "usage monitoring" as used by structural engineers usually refers to just flight condition monitoring, so that the "U" in HUMS has a broader connotation. Hence the acronym HUMS should be regarded as a convenient label rather than one which should be translated literally.

An Australian Defence Organisation Working Party has been formed to conduct "Strategic Planning for Helicopter Accident Data Recording and Maintenance Monitoring in Australia". Basically this working party aims to provide guidance to the Australian Defence Force (ADF) on the effectiveness of these recording and monitoring systems (especially HUMS) for use in ADF helicopters. The Working Party includes membership from all three services [the Australian Regular Army (ARA), the Royal Australian Air Force (RAAF) and the Royal Australian Navy (RAN)] and the Aeronautical and Maritime Research Laboratory (AMRL).

In 1992 the author visited several research establishments, manufacturers and military operators in the USA and the UK with the primary aim of gaining an insight into the opinions and plans of the international R&D community on the application of HUMS to military helicopters. It had been observed prior to the visit that usage monitoring within the context of HUMS had received much less coverage in the scientific literature than health monitoring. As a consequence special emphasis was placed on exploring the views of the international community on the relevance of the usage monitoring component of HUMS.

This document provides an overview of some of the important issues which military operators face and some initiatives they have taken in the HUMS area. Many of the issues are equally relevant for civil helicopter operators.

2. ACCIDENT DATA RECORDING

Integrated systems now coming into service in some civil helicopters combine the signal acquisition and processing functions for accident data recording with those for maintenance data monitoring using common equipment. The accident data recorder (ADR) normally includes both a cockpit voice recorder (CVR) and a flight data recorder (FDR). The maintenance monitoring element of these systems is usually referred to as HUMS. The relationship of HUMS to accident data recording is important in lieu of the approach being taken by equipment manufacturers to combine these elements in the same system.

The fitting of an ADR (comprising both a CVR and a FDR) is a mandatory requirement defined by some civil regulatory authorities and is likely to become a more widespread requirement around the world in the near future. For example, the fitting of a CVR has been mandatory for some time in the UK for medium and large helicopters on the civil register, and more recently (late 1992) the fitting of a FDR became mandatory. Civil operators are therefore more inclined to be looking at ways of offsetting the mandatory cost of fitting an ADR by combining it with HUMS which many believe will yield significant cost benefits.

Both the CVR and the FDR have special recording requirements. The recording medium must comply with the stringent environmental specifications for crash survivability and the data must be recorded as it is received (rather than in "blocks" which could result in the last vital seconds prior to the accident being lost). Systems currently available allow the cockpit voice and the flight data to be recorded on a single medium, either using the older magnetic tape recording technology or the more recent (and preferred) solid state digital recording technology. For the combined ADR and HUMS currently available from UK manufacturers, the ADR element absorbs about 70% of the overall acquisition system card space.

Military operators are not bound by civil regulatory authority requirements and are looking at ADR justification issues (safety, legal etc.) and cost very closely. The repeal in 1987 of the 1947 Crown Procedures Act, which opens the way for members of the armed forces and their families to sue the Crown for damages if negligence can be proved in accidents resulting in injury or death, is a major factor being considered by UK military operators looking at the ADR and HUMS issues. All military operators visited by the author in 1992 are grappling with the complex issue of merits versus cost of installing an ADR, exacerbated by the problem of shrinking defence budgets. The up-front purchase and installation costs are more difficult to justify in aging fleets.

UK Military Overview

The cost of the ADR is the issue of greatest concern, although it is believed that the ADR would provide valuable information to assist accident investigations. The Army is keen to fit CVRs in Lynx helicopters. There appears to be a considerable body of opinion which is inclined towards the fitting of stand-alone HUMS largely because it is believed HUMS may have more clearly definable cost benefits. However the cost benefit issue is still subject to

current investigations. A Bristow* FDR/CVR/HUMS [1,2] is to be fitted in a RN Sea King for evaluation. Gadd [3] (NAML) believes it unlikely that the RN will retrofit ADRs to its helicopter fleets. However the fitting of an ADR is a requirement for new military aircraft including helicopters.

US Military Overview

There is a strong US military thrust towards the fitting of FDRs in helicopters although the services are still deliberating on this issue. There appears to be little inclination towards the fitting of CVRs. At one stage the SH-60B Seahawk was the lead US service helicopter scheduled to have FDRs fitted The Smiths Industries FDR (referred to as a Standard Flight Incident Recorder [4]) was chosen for the SH-60B helicopter but recent advice indicated that the US Navy had discarded plans to fit this recorder. Bell Helicopter Textron representatives [5] indicated that the US Army planned to fit FDRs to all its helicopters eventually, but this has not been confirmed.

Representatives [6] of the US Army Aviation Applied Technology Directorate (Ft Eustis) indicated that the fitting of FDRs is less costly in aircraft with appropriate 1553 data buses and that the need for FDRs is greatest for helicopters with "glass" cockpits (which utilise interactive function-selectable display screens)**.

At one stage the US Army was planning to fit a system referred to as the Flight Data Recorder/Fault Analyser (FDR/FA) to its Black Hawk and Apache helicopters. This system was effectively a FDR/HUMS although the HUMS element needed considerable development over time. A version of the FDR/FA was also under consideration by the RAAF for use in the Australian Black Hawk. The US Army FDR/FA program for the Black Hawk and the Apache ran into financial difficulties, and it, together with the Australian program, was shelved. The airborne hardware was divided into an A kit (interface by aircraft manufacturer) and a B kit (Sundstrand units). The cost of the A kit was a major problem particularly in the UH-60A Black Hawk which does not have the 1553 data bus. It was considered feasible to fit the system in aircraft with the 1553 data bus such as the US Army OH-58D, MH-47E and MH-60K. Sundstrand has been contracted to supply 300 FDRs for installation in US Army Special Operations Aircraft (including the MH-47E and the MH-60K). This program is being coordinated by the Safety Group at Ft Rucker.

Canadian Military Overview

The Canadian government decided that the Department of National Defence would purchase 100 Bell 412 (four-bladed twin-engine Huey) helicopters for use in the light utility, transport and tactical roles. The purchase is an off-the-shelf buy, with the helicopters certified to civil standards requiring CVR and FDR equipment. The system to be installed is a variant of the SHL/Teledyne FDR/CVR/HUMS [7,8,9]. It includes the standard FDR and CVR, and the rotor

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* The Bristow FDR/CVR/HUMS is a joint development of Bristow Helicopters, GEC Marconi Defence Systems, Westland Helicopters (transmission diagnostics) and MJA Dynamics (rotor smoothing and diagnostics). It is referred to as the "Bristow" system for the sake of brevity.

** Older aircraft typically use analogue servo cockpit gauges which tend to "freeze" under crash conditions and allow some pre-crash information to be retained.

smoothing element of HUMS. Consistent with Canadian National Defence policy, the system will come with the provision for future growth of HUMS through local development.

3. HEALTH AND USAGE MONITORING SYSTEMS (HUMS)

3.1 General

The justification for the inclusion of any given element within HUMS is based principally on whether it provides:

- Enhanced airworthiness (reduced risk of in-flight failure).
- Maintenance cost benefit.
- Increase in aircraft availability.
- Combination of the above.

The airworthiness benefit of HUMS has been highlighted in a recent news item [10] which states: *"A Boeing 234 operated by Norway's Helikopter Service was prevented from taking off when its health and usage monitoring system (HUMS), made by Stewart Hughes Ltd. and Teledyne controls, detected abnormal vibration before takeoff. Inspection showed that the vibration was caused by a cracked safety bolt. This may be the first time that a potential accident was averted by an on-board HUMS".*

3.2 Health Monitoring Issues

3.2.1 Engines

Most operators regard the provision of take-off power assurance as an essential feature of HUMS. Such assurance is normally required daily and, in the absence of HUMS, this function is usually performed manually according to the engine manufacturer's specified procedure. HUMS presently in service on civil helicopters provide take-off power assurance indication.

Other engine health monitoring techniques which are candidates for HUMS are oil debris monitoring, performance trending and vibration monitoring. Engine vibration level is displayed in the cockpit during flight in currently installed HUMS.

SHL [11] has been involved in the development of gas path monitoring systems referred to as the Engine Distress Monitoring System (EDMS) and the Ingested Debris Monitoring System (IDMS). EDMS detects electrostatically charged particles in the engine exhaust and IDMS detects debris and foreign objects ingested via the intake. It is claimed that combined EDMS and IDMS can differentiate between particles generated within the engine and particles ingested via the intake. Colucci [12] outlines development work by Smiths Industries on an Electrostatic Engine Monitoring System (EEMS) which functions like the EDMS. Although currently available HUMS do not provide these advanced gas path monitoring capabilities, Daly [13] reported that Sikorsky, who is to assess bids for providing HUMS for its S-76 helicopters, will be aiming to provide optional inclusion of an electrostatic engine monitoring system.

Many of the health monitoring techniques developed for engines in fixed-wing aircraft are equally applicable to helicopter engines. Some of the relevant technologies are fairly mature whereas others (e.g. EDMS and IDMS) are not. Engines are relatively high maintenance items and improved health monitoring via HUMS is considered likely to return cost benefits. In particular, the application of on-condition monitoring to some components, in lieu of replacement after a specified number of operating hours, is widely considered to be a potential source of significant cost benefits.

3.2.2 Transmission System

Enhanced safety provides the main motivation for including transmission health monitoring in HUMS. Failures in the transmission system rate second only to those in the rotor system in terms of causing airworthiness-related accidents in helicopters. Some maintenance cost savings may be realised by early detection of some faults which could result in secondary damage if not attended to promptly. However, as the transmission system is not normally regarded as a high maintenance area, major maintenance cost savings are unlikely to be realised.

Transmission system health monitoring is considered below in terms of vibration monitoring, oil debris monitoring and temperature monitoring.

Vibration Monitoring

All military operators visited by the author in 1992 consider some form of transmission vibration monitoring to be an essential ingredient of HUMS. A major problem with transmission vibration monitoring is the lack of genuine fault data to allow algorithm verification and assessment. Vibration monitoring provides the only early-detection method for those failures (e.g. fracture) which do not shed debris and hence are not detectable by debris monitoring systems.

Vibration monitoring is considered desirable to enable assessment of:

- Condition of main, intermediate and tail gearbox bearings and gears.
- Balance and alignment of main gearbox high speed input shafts and tail rotor drive shaft.
- Hanger bearing condition.

Some of the opinions expressed during the author's 1992 visit to the USA and the UK were:

- Bell Helicopter Textron engineers 5 were of the view that the development of algorithms was fairly mature but there was an urgent need to validate them.
- Bell Helicopter Textron engineers were of the opinion that emphasis should be placed on monitoring the condition of single drive path transmission system components. They expressed the view that failures in multiple drive path components (e.g. epicyclic gears) are likely to be detected by other means before a catastrophic failure occurs.
- Sewersky [14] (Sikorsky) considered vibration monitoring as a catch-all for the mistakes which could occur during maintenance action.
- US Army representatives [6] (AATD) expressed confidence only in low frequency vibration analysis for shaft misalignment.

- Gadd [3] (NAML) considered that transmission vibration monitoring was sufficiently mature and that far more emphasis should now be placed on implementing algorithms than on their further development.
- James [15] (CAA) indicated that vibration monitoring gives an earlier warning of a failure in a hanger bearing than temperature monitoring and has shown good capability as the primary indicator of such failures.

Most military operators consider that transmission vibration analysis would lower the risk of accidents due to failures in the transmission system but that it would be difficult to establish substantial cost benefits.

Oil Debris Monitoring

Wear monitoring is considered by all the military operators, visited by the author in 1992, to be an essential feature of HUMS. They already use some form of gearbox wear monitoring for early-failure detection particularly of bearings.

Some of the main technologies available are:

- Chip Plug
  - ☐ Simplest of available techniques.
  - ☐ Technique accepted by everybody.
  - ☐ Can be ineffective (particularly when debris would need to pass through multiple bearings to reach the chip detector).
  - ☐ In respect of Sea King, Gadd [3] (NAML) commented that the chip detectors used for the intermediate and tail gearboxes are very sensitive, whereas those for the MRGB are "all over the place" and detect only 50% of the failures which shed debris (the problem here being that much of the debris may not reach the detector due to "obstacles" such as bearings in the path to the detector).
  - ☐ Provides the latest warning of all debris monitors.

- Spectrometric Oil Analysis
  - ☐ In-flight oil sampling and analysis are impractical.
  - ☐ Has provided good results for engines.
  - ☐ Helicopter gearbox application is less advanced.
  - ☐ Has been used extensively by the UK services.
  - ☐ Andrew [16] (MJAD) was able to identify problems in a number of gearboxes using a parallel analysis of data from a large number of gearboxes.
  - ☐ Correlation with HUMS analyses is considered desirable (Spectrometric Oil Analysis is not a candidate for on-board HUMS).

- On-Line Debris Monitoring
  - ☐ Can look at the full range of particle sizes.
  - ☐ Some systems can detect non-ferrous particles.
  - ☐ Is a prime candidate for HUMS.
  - ☐ Difficulties have been experienced with commercially available systems evaluated in HUMS trials in the North Sea area.
  - ☐ Currently installed HUMS do not include on-line debris monitoring.

- The Bristow HUMS is programmed to accept the output from the Tedeco QDM (quantitative debris monitor) and that system is likely to be included [17] in the next version of the Bristow HUMS.

Wear debris monitoring, like most forms of health monitoring, is airworthiness-driven and cost benefits are therefore difficult to quantify.

Temperature Monitoring

Temperature monitoring has been used in experimental installations for early failure detection of tail shaft hanger bearings which are not immersed in oil. Because temperature monitoring provides a late indication of a failing bearing, it is generally regarded as a secondary rather than a primary indicating system.

3.2.3 Structural Components

In the context of this document structural components are considered to include:

- Rotor blades, hubs, controls etc.
- Rotor shafts (usually part of gearboxes) and gearbox housings.
- Airframe.

Rotor system health monitoring will be considered separately in terms of *rotor smoothing* and *rotor diagnostics*:

Rotor Smoothing

Rotor smoothing is the optimum adjustment of rotor track and balance to minimise vibration levels experienced by the airframe. The relative tracking of the rotor blades is trimmed via pitch rod length adjustments on each blade. Rotor balance is trimmed by adjusting the magnitude and position of mass-balance weights installed on each blade. Rotor smoothing is a very high maintenance area for helicopters and, as a result, plenty of in-flight airframe vibration data have been available for the development and verification of the required algorithms. Rotor smoothing is seen by all operators to be a clear candidate for HUMS. It was pointed out by Pipe [18] (SHL) that rotor smoothing typically absorbs 5% of overall flight time at present (when HUMS is not in use) and the figure could be as high as 12% for the Chinook helicopter. The basic aim of its incorporation in HUMS would be to remove the necessity for dedicated maintenance flights for rotor smoothing.

Rotor smoothing technologies are fairly mature although far from simple. Day-to-day variation of airframe vibration signals occurs due to the effects of variations in outside air temperature and altitude on air density. The amplitude of the blade passing frequency component can vary by as much as 30% from day to day. The day-to-day effects need to be removed for smoothing purposes. Andrew and Azzam [19] have made significant advances in "filtering out" the day-to-day variations from the rotor smoothing analysis.

It is now known that metal blades are more consistent in their in-flight behaviour than composite blades, with the absorption of water in the latter being one problem. With the trend towards the use of composite blades this problem is becoming more prevalent.

Rotor track and balance adjustments need to be small so that an error by a maintenance technician in making an adjustment in the wrong direction or on the wrong blade will not cause a major problem.

Rotor smoothing is incorporated in the Bristow [1,2] and the SHL/Teledyne HUMS [4,7,8]. Both systems require an external tracker to be fitted for assessing the required balance adjustments. The Bristow system employs a permanently installed tracker whereas the tracker is only installed for the SHL/Teledyne system when the measured vibration levels indicate that a tracking check should be done. Trackers work by using triangulation to determine the relative flying height and lag of each blade as it passes over photo-sensors.

TII considers both track and balance adjustments can be assessed using only airframe vibration data. Such an arrangement would make it easier to maintain serviceability since an optical tracker (which in other systems has to be mounted externally where harsh operating conditions prevail) would not be required. However the redundant information provided by systems which incorporate a tracker is seen to be an advantage by some operators.

Typically about six airframe-mounted accelerometers are required to collect vibration data for smoothing both main and tail rotors. Accelerometers are generally very robust and reliable sensors.

It is essential that track and balance measurements be made under defined conditions, such as during steady forward flight or hover. Because a satisfactory means of identifying low speed flight conditions is not available, current systems require pilots to initiate some of the measurements.

Rotor smoothing within HUMS is seen to have the potential to provide significant benefits. The benefit alluded to above is the realisation of a direct reduction in the amount of flying time specifically dedicated to smoothing the rotors. This would improve aircraft availability which could be translated as a gain in hours for normal operations or a decrease in running costs if the hours for normal operations were not increased. The HUMS philosophy is to monitor, during normal operational flying, the rotor track and balance adjustments required to minimise airframe vibration levels experienced by the aircrew and the aircraft equipment. By maintaining low vibration levels, crew comfort can be enhanced and damage to avionics equipment minimised. The main damage to helicopter avionics is caused by vibrations at fundamental rotor frequency. It has been claimed that a doubling of avionics equipment life may be achieved with good rotor track and balance control. Because military aircraft tend to be fitted with very sophisticated and expensive avionics, this potential benefit is particularly important for military operators.

Rotor Diagnostics

A number of researchers (including Andrew [16] of MJAD and Ventres [20] of TII) are working on the development of diagnostics for detecting certain faults in rotor systems using the same airframe vibration data collected for rotor smoothing purposes. However the development of rotor diagnostics is not considered to be very mature. James [15] (CAA) identified it as that element of health monitoring which is most in need of further research and development. The deficiency is seen as a reflection of the difficulty of the diagnosis rather than its importance, as

rotor system failures are by far the most significant cause of structural airworthiness problems in helicopters. Developments have been hampered by the dearth of rotor system fault data.

For rotor diagnostic purposes, Azzam and Andrew [21] make use of a rotor system mathematical model which can treat each blade, pitch link etc. differently. Generic type algorithms are unsuitable for analysing the condition of rotor blade lead/lag dampers; specific algorithms are usually required for each helicopter. MJAD has applied the mathematical dynamic models to analyse a range of faults including blade fracture development, binding or jammed hinges, difference between dampers, blade or elastomeric bearing incompatibility problems, control system irregularities and lifting (debonding) of blade leading edge strips. In respect of blade fracture, Andrew [16] (MJAD) found that fracture development in a rotor blade induced a change in the natural frequencies of the blade.

Other

Very few developments have been made in the area of structural health monitoring, considered here to mean the early detection of cracks in structural components or airframe.

Cracks in the metal spars of rotor blades are frequently detected with the aid of gas leakage detectors. Similar gas leakage detectors have been considered for use with flight control linkages. Gas leakage detectors in current service provide a visual indication of crack status and need to be regularly inspected. As these detectors do not provide an electrical signal to reflect fracture status, they cannot, in their present form, be monitored by HUMS.

Some promising research into methods of detecting cracks in structures is being undertaken at present:

- As noted above, MJAD is looking into the detection of cracks in rotor blades using an analysis of airframe vibration signals.
- Kaman Aerospace Corporation [22] is examining the use of redundant load sensors to provide some structural health diagnostics. When a fault (e.g. a fatigue crack) develops it is likely that the relationship between loads developed at different locations will change and redundant load sensors may be able to track such a change.
- *Smart structures* which make use of permanently embedded sensors (e.g. optical fibres) are under examination. It is assumed that the sensor will fracture with the structure and hence be able to provide an indication of failure.

The above crack detection technologies, which are undergoing early stages of development, may have future application to HUMS but are not considered mature enough for inclusion in present HUMS.

3.3 Usage Monitoring Issues

Usage monitoring is applicable to helicopter components whose fatigue lives are limited according to *safe-life* design principles. The safe-life approach is prevalent for highly loaded metallic components commonplace in helicopters. Components with designated safe lives are always replaced when their safe-life limit is reached, even if their "health" (e.g. in relation to rotor blade or transmission gear fracture) is being monitored. With the exception of

exceedance monitoring, usage monitoring has not received much attention to this time in the HUMS area. With greater emphasis being placed on HUMS cost effectiveness, usage monitoring is likely to receive much more attention in the near term. Usage monitoring issues will be examined in relation to the engines, transmission gears and structural components.

3.3.1 Engines

Both exceedance monitoring and cycle counting (rotational speed and temperature) have been used fairly extensively on engines in both fixed and rotary-wing aircraft. In every case the engine manufacturer's algorithms are applied to convert engine cycle counts to component life expenditure.

Low cycle fatigue (LCF) is the form of loading prevalent for life-limited engine components. The replacement of engine components according to the severity of in-service usage for individual engines has been accepted by engine manufacturers for a considerable period. However engine cycle counting is sometimes used only to confirm or amend component retirement times (expressed in terms of operating hours).

Some military operators believe engine usage monitoring will yield significant cost savings. To gain optimum benefits from usage monitoring, components need to be replaced according to measured usage for individual engines and an associated system of component life tracking needs to be in place. Nurse [23] (MOD-PE) postulated that an average 30% increase in lives of life-limited engine components, and corresponding cost benefits, could accrue from implementation of engine usage monitoring. Engine usage monitoring can be incorporated as an integral part of HUMS or via a dedicated engine-mounted system.

3.3.2 Transmission System

Some transmission system gears in some helicopters are fatigue life-limited. Furthermore it is fairly common for gear durability to limit the engine power available to the rotor system over much of the helicopter operating envelope.

All helicopters provide an indication of the level of torque developed by each engine, and hence torque sensing is always included. The most common fatigue failure mode for gears is fracture at the tooth root for which the cyclic bending load at shaft frequency is the significant fatigue load. The bending loads are proportional to transmitted torque. Engine torque thus provides a direct load measurement parameter for MRGB gears (although tail take-off torque needs to be deducted for some). Unfortunately engine torque is a difficult parameter to measure accurately. Hydraulic torque sensors in many older helicopters are subject to large measurement inaccuracy (up to 10%). Such systems have been used in most WHL Sea King helicopters but the latest version of the aircraft has a strain gauge telemetry torquemeter for engine torque measurement. In recent times, engine manufacturers have been building torque sensors into the basic engine These sensors measure engine shaft angle of twist and are purported to provide much improved accuracy (close to 1%).

In helicopters where gear durability is of significant concern, gear usage monitoring may provide a number of benefits. These include:

- Performance enhancement by allowing normal torque limits to be exceeded on the basis that the effect of such exceedances are monitored and taken into account.
- Avoidance of some gearbox removals which, without usage monitoring, would have been required on the basis of the uncertainty associated with pilot reporting of the magnitude and duration of an overtorque.
- Life extension of individual gears if their lives are based on the actual severity of in-service usage.

Gadd [3] (NAML) was of the opinion that measurement of engine overtorque by HUMS would provide clear savings for the Sea King helicopter, because current practice is to assume the "worst case" if a pilot cannot clearly identify the level and duration of the overtorque. The RN has replaced many fatigue life-limited gears in Sea King and hence the replacement of individual gears according to the severity of in-service loads is likely to return cost benefits.

Other transmission rotating components which carry aerodynamic loads (e.g. main and tail rotor shafts), and some non-rotating components (e.g. the main rotor gearbox housing which, in most helicopters carries airframe structural loads) are considered under *Structural Components*.

3.3.3 Structural Components

The scope of structural components considered here conforms to the definition provided in Sec. 3.2.3.

Normally the majority of fatigue life-limited components in helicopters are in this category. Up to the present time most structural fatigue specialists have considered available technologies in the context of stand-alone monitoring systems. Most of the arguments which apply to stand-alone systems are equally valid for HUMS. The main technologies are reviewed below.

With a growing demand to demonstrate HUMS cost effectiveness there has been a strong trend in recent times to put greater emphasis on the usage monitoring element of HUMS. During the first half of 1993 the CAA (UK) set up a Usage Monitoring Working Group (UMWG) under HHMAG to investigate the extension of usage monitoring capabilities within HUMS. The UMWG delivered its final report [24] to the HHMAG in 1993.

Flight Condition Monitoring

Flight Condition Monitoring (FCM) involves measuring the time spent in each of a set of defined flight conditions and the number of times the flight condition is entered. If gross weight can vary significantly for different missions, as it often does in military applications, weight monitoring is also usually deemed to be required. Alternatively, the maximum gross weight could be assumed to apply for all missions, but that may result in overly conservative component life estimates. FCM is normally referred to as *usage monitoring* by structural engineers but, as indicated earlier, a broader definition of usage monitoring is used in this document in the context of HUMS.

The helicopter manufacturer usually defines a set of flight conditions applicable to each helicopter. The number of defined flight conditions varies from manufacturer to manufacturer and from helicopter to helicopter, but a value in excess of 50 would be typical. For most life limited components the important fatigue loads occur at rotor fundamental frequency or a multiple thereof. In such cases the number of load applications can be calculated if the time spent in the flight condition is known. In other cases, the load cycle of interest is the entry to and exit from the flight condition and in such instances flight condition occurrences need to be counted.

To calculate component life expenditure from flight condition data, the transfer characteristics between flight conditions and the amplitudes of component loads need to be known. Such characteristics are usually derived by the aircraft manufacturer in a flight loads survey on the prototype helicopter. To ensure calculated lives are conservative, it is essential that maximum loads, for the various flight conditions, are developed in the survey. Military operators are concerned that the severity of loads developed when helicopters are flown by their pilots may differ significantly from those developed in the manufacturer's loads survey. In the context of HUMS, the operator may have to undertake further load tests to validate the transfer functions relating flight conditions to loads.

FCM provides the simplest means available to quantify the life expenditure of individual components. Many of the parameters required to identify flight conditions are sensed and measured by the standard aircraft circuits. The need for special sensors is therefore small, and most of those parameters which do require special sensors (e.g. vertical acceleration) can be measured with better reliability than those parameters required for direct load measurements.

One major problem is the identification of low speed flight conditions (e.g. hover entry and exit). The problem is exacerbated by the inability of current technology airspeed sensors to measure speeds below about 30 knot in the helicopter environment. Unfortunately some of the major fatigue damaging loads are developed in low speed manoeuvres.

Automatic logging of gross weight would, in most cases, be a FCM requirement. A number of researchers have been investigating algorithms to estimate gross weight from measured flight condition parameters, but further validation is required. Bell Helicopter Textron engineers [5] indicated that they favoured the use of load sensors on the undercarriage for gross weight estimation.

FCM requires that the relevant parameters be monitored all the time. Typically FCM would generate about one megabyte of data per hour if the flight condition recognition were to be performed at a ground station. The generation of large quantities of data requiring ground station processing is generally viewed very unfavourably and to be avoided as much as possible in the HUMS environment. Hence in-flight recognition of flight condition may be essential for the HUMS application. In-flight recognition of helicopter flight condition has been achieved by Sikorsky and MDHC. The extension of the airborne software to allow component life expenditure calculation to be performed in flight could be considered.

Flight Loads Monitoring

Direct flight loads monitoring (FLM) provides the best form of data from which component life expenditure can be confidently calculated. The need to recognise flight conditions and

measure gross weight would be eliminated if comprehensive loads monitoring were used. Directly measuring critical loads on each fatigue life-limited component would never be considered. Instead, it is sufficient to measure a selected sub-set of substantiating loads, from which the critical component loads can be deduced. The safety factors, which need to be included with FCM to ensure that the estimated loads are conservative, could be relaxed if FLM were used.

However, some perceived difficulties with FLM include:

- **Load Measurement Reliability:** Obtaining reliable load measurements over extended periods in the operational helicopter environment is extremely difficult (or perhaps totally impractical). The load measurement problem is exacerbated for those rotating components which require special signals to be transmitted from rotating sensors to stationary receiving equipment.
- **Special Nature of Installation:** There is greater commonality among various helicopter types for FCM parameters than for component load parameters. Special sensors are required for each load parameter. The sensor locations and the signal transmission requirements for the load parameters would tend to be specific to each aircraft type.
- **Retrospective Life Calculation:** Sometimes, following unforeseen fatigue problems discovered through in-service experience, further components are added to the list of life-limited components. FLM may not enable retrospective life calculations to be made. In contrast, FCM would allow such retrospective calculations to be made, if the flight condition to load transfer characteristics are established and flight condition data have been retained.

Loads monitoring has been successfully implemented in fixed-wing aircraft, but it is recognised that the rotary-wing environment presents much greater difficulties. However, research such as that currently being undertaken at Kaman Aerospace by Gunsallus [25,26] at al, on synthesising the rotating system component loads from static system loads, may overcome some of the major concerns relating to the practicality of measuring the required loads in the operational environment. The synthesis technique provides significant scope to place load sensors in benign locations and to minimise the number of sensors required. Four strain gauge measurements can typically be used to synthesise the time histories of 20 loads. A stand-alone system [27], commercially available from Kaman Aerospace, performs most of the data processing in flight, an approach highly favoured by many for HUMS applications.

Andrews of MJAD has been undertaking promising research on a transfer function technique which directly relates the fatigue life expenditure of rotating or fixed system components to fixed system loads.

As the application of the Kaman and MJAD techniques is relatively new to the helicopter structural integrity application, there is great interest in further assessing the merits of these methods as they mature.

There may be scope to consider a hybrid form of usage monitoring including both FCM and FLM.

Benefits of Structural Usage Monitoring

Appropriately applied fleetwide structural usage monitoring would ensure that any components which are loaded more severely than the assumed design usage would have their lives correspondingly shortened so that safety of operation is not compromised.

Most military operators believe that structural monitoring has considerable cost savings potential. That potential is increased if the helicopter has a large number of costly low-life components. High aircraft utilisation favours the realisation of cost benefits. The arduous nature of many military operations may contribute to reduced retirement lives for some components but the effect of the reduction is partially neutralised if the aircraft utilisation is low (which is frequently the case for military helicopters in peacetime)..

Fleetwide structural usage monitoring, via a HUMS (or other permanently installed system) would provide a large database which, presumably, could be used for substantiating component lives (expressed in operating hours). Furthermore, the large database should permit the lives of some components to be extended if the severity of usage were lower than that specified in the design spectrum. (The size of the database generated in conventional short term life substantiation programs, involving only a small number of aircraft, is often considered to be too small to warrant an extension of the lives of any components.) Hence HUMS could yield some cost benefits via component life extension. However, worst case lives would still have to be specified.

The other approach to gaining cost benefits, and the one most military operators thought had the greatest promise, would be to retire individual components according their measured life expenditure. To implement such an approach it would be necessary to introduce parts life tracking (PLT), which in this context refers to an information management system which would keep track of the life expenditure status of individual components. A separate direct flight loads monitoring program may need to be undertaken to identify the components whose lives are worth tracking. Generally, it is regarded as essential that PLT be integrated with logistics management to control the supply and distribution of spares. Because PLT requires that account be taken of component life expenditure during all flying time, it is essential that an appropriate substitution be made for any data lost when the HUMS is unserviceable.

The application of PLT to very large fleets presents great difficulties. Some US Army representatives doubt whether it is practical to apply it to US Army fleets. The US Navy plans to fit stand-alone structural usage monitors in all its helicopters and proposes to apply PLT.

The introduction of PLT would require the support of the helicopter manufacturer. This is seen as a major stumbling block for a number of military operators. Sewersky [14] (Sikorsky) and Duthie [28] (WHL) have indicated that manufacturers recognise the growing customer demand for HUMS cost benefits and future helicopters are likely to provide for PLT. The support for PLT for current helicopters is considered to be a more complex issue but Duthie indicated that WHL would support its application to Sea King, although more detailed stress analyses of some components would be required.

3.4 System Issues

Some issues which may broadly affect the operation or the form of the recording and maintenance system that military operators may choose for their fleets, are considered below.

3.4.1 Integration Benefits

Both the FDR (for accident data recording) and the HUMS usage monitoring element require continuous reading of input data during flight and hence both require permanently installed systems. Many of the parameters included in the FDR parameter list are also required for structural usage monitoring (via flight condition recognition). The inclusion of both these systems in the same unit would enable the sharing of some common features.

A reliable means of flight condition recognition could be used to enable automatic initiation of data collection for rotor smoothing and transmission vibration analysis. Pilot initiation of the collection of some of the required data is used in currently available systems.

It is widely agreed that improved reliability in early failure detection will result if a number of independent diagnoses (e.g. vibration analysis and oil debris analysis) point to the same fault. It is highly desirable that the health monitoring system be capable of making some automatic health assessments using information from multiple sources.

3.4.2 System Configuration Options

Military operators are considering the merits of optional configurations which do not constitute a fully integrated CVR/FDR/HUMS. It is likely that, in some instances, a stand-alone HUMS will be chosen, basically because the CVR and FDR are considered too costly for retrofitting to some helicopters. Pipe [18] (SHL) indicated that the cost of the HUMS airborne element of the SHL fully integrated CVR/FDR/HUMS represented about one third of that for the complete system. A stand-alone HUMS is not presently commercially available although it is likely that such a system will soon become available for the military market.

Declared military policy for future helicopter purchases in the UK and Australia is that a CVR and a FDR must be fitted. Hence in these cases the justification for fitting HUMS can be viewed in the context of it being an add-on to the CVR and the FDR, much like it is for civil helicopters.

Military operators currently use portable systems for periodically smoothing rotors and, in some instances, for collecting transmission vibration data for later analysis. The use of such systems is likely to continue for many helicopter fleets, particularly those which are not likely to remain in service for a long period. The portable system option is available only for health monitoring. If the portable health monitoring system option is chosen, then usage monitoring, if adopted, requires the incorporation of a stand-alone permanently installed system. Many are of the view that the days when one would employ a multiplicity of "black boxes" for these functions are drawing to a close.

3.4.3 Extent of In-Flight Processing

The opinions of military operators vary on the desirability of maximising in-flight processing. Reasons for maximising in-flight processing are:

- Maintenance overheads are reduced if the amount of data requiring ground station processing is minimised.
- The results of any analyses which provide advice on airworthiness should be "immediately" available after flight, and this is facilitated by more in-flight processing.
- Computer-related technologies are well advanced and capable of performing most of the processing during flight very reliably.
- When HUMS technologies further mature, in-flight processing will be essential if cockpit warnings are to be conveyed.

On the other hand, reasons for reducing in-flight processing are:

- Retention of the maximum amount of unprocessed data is important, at least until technologies have been further verified.
- The incorporation of software upgrades would be simpler and less costly if ground analysis is maximised.

3.4.4 Monitoring System Reliability

The likelihood of a fault developing in the monitoring system is usually much higher than that of one developing in the mechanical/structural system being monitored. Parameter sensors are more prone to problems than most other elements of the monitoring system. Generally microprocessor and electronic systems are reliable but the electrical connections to these systems have been prone to problems. One of the major requirements of the monitoring system is that it be capable of checking data integrity so that wrong decisions are not made because of bad data. Furthermore this checking process should be automated to the maximum extent possible. This area seems to have received only minor attention to date and is seen as one requiring further research.

The reliability of the recording media used in the monitoring system is also an issue. While magnetic tape recording is still used in the CVR/FDR element of currently installed systems, solid-state storage systems are now available. The HUMS element of the Bristow system uses a solid-state removable memory module. In the relatively short term it is anticipated that new systems will utilise only solid-state storage with an associated improvement in reliability over magnetic tape systems.

3.4.5 Cost Effectiveness

Quantifying the cost effectiveness of HUMS, while obviously essential, is also generally difficult.

The placing of a monetary value on improved safety is particularly difficult. Pipe [18] (SHL) indicated that a figure of USD 80 per flying hour has been accepted by North Sea civil helicopter operators as the value attributable to the overall improvement in safety expected to be achieved through the fitting of HUMS. It is probably easier for civil operators to place a monetary value on safety improvement if the fitting of HUMS is reflected by a reduction in

insurance premiums and by the provision of maintenance credits. Military operators, by contrast, do not normally insure their aircraft and have to define realistic cost savings attributable to a decreased risk of losing an aircraft for airworthiness reasons.

The areas identified as having the greatest maintenance cost benefit potential were:

- Rotor Smoothing: Elimination of special maintenance flights.
  Extended life (especially of avionics) by better vibration control.
- Engines: "On-condition" component replacement.
  Life on cycles.
- Transmission: Avoidance of some overhauls because of unknown over-torque.
- Structure: Avoidance of over-conservative component retirements.
  Parts Life Tracking.
- General: Extension of time between inspections, servicing and overhauls.
  Automatic logging of flight time.

3.4.6 Information Management

Information management is the application of various technologies to extract results and convey them to the end user in a suitable form. For HUMS, information management would include such system processing elements as:

- Automatic scheduling of the application of health and usage algorithms.
- Combining the results of different forms of analysis (e.g. vibration and oil debris analysis).
- Coordinating and presenting maintenance advice.
- Screening and taking account of bad data, and flagging monitoring system faults.
- Parts life tracking and interfacing with logistics management schemes.
- Automatic processing of other data.
- Archiving of selected data.
- Coordinating and maintaining fleet status records.

Ground station facilities are essential for some of these processing functions.

Information management is an area that has not received adequate attention to this time. One of the main concerns of operators is that HUMS may become a gatherer of a huge amount of data which cannot be handled. According to Duthie[28] (WHL), this appears to be happening, to some extent at present with much of the data generated by the HUMS in civil service "being put away in the cupboard". James[15] (CAA) considers significant improvements in HUMS information management will be necessary before the civil helicopter safety target of 10^{-7} accident per hour can be achieved for civil helicopters.

The use of advanced information monitoring techniques such as Artificial Intelligence (AI) is being considered by some HUMS researchers. Andrew[29,30] (MJAD), who has developed the rotor smoothing and diagnostic software for the Bristow HUMS, regards machine learning as an important element for HUMS, as "too much data are acquired for the human operator to

analyse". Because rotor smoothing is a high maintenance area it becomes a lead candidate for the application of machine learning techniques. Leading researchers are also proposing the application of AI techniques in the usage monitoring area.

The use of on-line machine learning techniques in the area of early failure detection is not generally favoured because of their non-deterministic nature. Verification of non-deterministic processes is the major problem. However the application of machine learning techniques to find the best way of automating the application of a range of algorithms is seen as an advantageous step prior to writing the diagnostic software in a deterministic manner.

3.4.7 Other

The ability to expand and/or upgrade the capabilities of installed HUMS is considered to be desirable. This is especially important because HUMS technologies are still emerging.

A contentious issue is whether there should be provision for the customer to extend or change HUMS software. US Navy representatives [31] are strongly of the opinion that HUMS software must be "open" to allow change by the customer. TII has been contracted by the US Navy to supply a HUMS which incorporates open software. Currently available HUMS do not incorporate open software.

HUMS presently being installed in civil helicopters have not been qualified to meet military specifications, although the CVR/FDR must obviously meet a very harsh environmental specification. HUMS is not essential for combat or for mission capability (i.e. a successful execution of a mission would not be compromised if the HUMS unit were inoperative before the mission commenced or if it were disabled during the mission). There may be grounds for not demanding that military HUMS meets full military avionics specifications. Maybe a slightly upgraded civil version would suffice, and would be less costly that a fully militarised version.

Some military operators see great benefit in a system which could provide a prompt and reliable assessment of the condition of each helicopter, in terms of available safe operating hours for life-limited components and component health status, to aid the optimum selection of aircraft for combat duties. HUMS is seen to have considerable potential in this important area.

Gadd [3] (NAML) and Tansey [6] (AATD) are of the opinion that the recording of flight time (the time weight is off the wheels) via HUMS will lead to cost savings. They indicated that flight time is currently based on pilot logs which tend to err on the side of over-estimation.

4. MILITARY INITIATIVES

While the implementation of accident data recording and HUMS in civil helicopters is leading that for military helicopters, there is widespread military interest as evidenced by a variety of initiatives in the area.

The following test or implementation programs are either in progress or planned:

- The Royal Netherlands Air Force has ordered[32] seven SHL/Teledyne CVR/FDR/HUMS for use in its Chinook helicopters (and the contract includes an option for a further six systems).
- The Canadian DND has ordered a partial SHL/Teledyne CVR/FDR/HUMS to be fitted to the 100 Bell 412 light utility helicopters which it is purchasing. The DND proposes to implement further health and usage capabilities within this system in the future.
- The RN undertook a one-year trial of a Bristow CVR/FDR/HUMS in one of its HC.4 Sea King helicopters on behalf of all three services. The trial was completed in October 1993.
- An aircraft-specific health and usage monitoring system is to be incorporated in the EH101 helicopter to be supplied by Agusta/WHL for the RN.
- The US Navy is evaluating HUMS technologies on a test-bed at NAWC Trenton and in-flight on a SH-60 series Seahawk at NAWC Patuxent River. The HUMS being evaluated is supplied by TII. The evaluation includes AMRL's transmission vibration analysis and engine performance assessment algorithms.
- Under a collaborative program managed by the RAF, it is proposed that advanced usage monitoring techniques be evaluated in a flight demonstrator system to be fitted to the CH-47D helicopter. The system is referred to as a Fatigue Usage Monitoring System (FUMS) and is seen as a pre-cursor to filling the usage monitoring void in HUMS by the turn of the century. Participants in the FUMS program include the RAF, the US Army, the RNLAF, the ADF and industry.

A number of military working groups have been set up to investigate effectiveness or implementation issues for HUMS and accident data recorders. The following groups have been identified:

- A tri-service Helicopter Health and Usage Monitoring Implementation Group (HHUMIG) is operating in the UK.
- The RN had set up an EH101 Health and Usage Monitoring (HUM) Working Group. One of the major activities of this group was to bring together the objectives, definition and programs for health, usage and status monitoring of the EH101.
- The US Army has an Army Aviation Maintainability Strategy Study Group looking into health and usage monitoring requirements for US Army helicopters.
- The Australian Defence Organisation has a tri-Service Working Party to provide guidance on the effectiveness of integrated accident data recorders and maintenance monitoring systems for ADF helicopters.

A Study Assignment "Effectiveness of Helicopter Health and Usage Monitoring Systems in the Military Environment" (Annex A) has been set up within TTCP HTP-7 with the author (the AMRL member of the Australian Working Party) as the coordinating officer. This will provide one avenue for participating organisations to gain access to data on the initiatives and findings of in the HUMS area, and this should be beneficial to all participants.

5. CONCLUSIONS

(a) Multi-function systems now coming into service in some civil helicopters combine the functions of accident data recording and HUMS using common equipment. Similar systems are on order by some military operators and are being evaluated by others.

(b) The fitting of an accident data recorder, comprising cockpit voice and flight data recorders, is a mandatory requirement defined by some civil regulatory authorities and is likely to become more widespread in the future. Military operators are not bound by civil requirements but are seriously considering the fitting of accident data recorders in their aircraft. UK and Australian military operators have declared policies to fit them to new aircraft.

(c) Military operators are concerned about the high cost of accident data recorders, which typically account for some 2/3 of the cost of the multi-function airborne hardware now coming into civilian helicopter service. The problem is accentuated if retrofitting to helicopters currently in service is considered.

(d) HUMS health monitoring technologies for the transmission and engine systems are fairly mature, and selected technologies are incorporated in current commercial HUMS. Rotor track and balance is also well handled in these HUMS but diagnosis of other rotor system faults has been identified as an area requiring much more research and development. The verification of health diagnostics and the development of a suitable means of interfacing with military aircraft maintainers continue to be health monitoring areas requiring much more attention.

(e) HUMS usage monitoring has received far less attention than health monitoring. This appears to have occurred because the main emphasis to this time, for civil helicopters, has been on airworthiness aspects rather than cost benefits. Usage monitoring in currently available HUMS is limited to exceedance monitoring. Usage monitoring appears to be regarded as being more important for military than for civil operators, probably because there is a perception that, in general, military operations are more severe and more difficult to quantify than civil operations.

(f) Military operators see great airworthiness benefit from health and usage monitoring techniques which provide warnings of impending failures and ensure that fatigue life-limited components are replaced before the risk of failure becomes unacceptable, but consider the fitting of HUMS can only be justified if quantifiable cost benefits can be demonstrated.

(g) The elements of HUMS which most military operators perceive to have the greatest potential for direct maintenance cost benefits are:

- Automated rotor smoothing which eliminates the need for special maintenance flights, and provides better overall vibration control with an associated reduction in avionics maintenance costs.
- Retiring of some engine components according to counted cycles and others *on-condition*, rather than in terms of operating hours.

- Torque monitoring of main gearboxes which provides quantitative data on overtorques and therefore indicates which overtorques necessitate removal and overhaul of the gearbox.
- Structural usage monitoring if a system of component life tracking is also implemented.
- Extension of time between inspections, servicing and overhauls because of better health and usage monitoring.
- Accurate logging of flight time to avoid errors introduced by the current conservative practice of rounding up flight time.

(h) A major concern of military operators is that HUMS will become a large generator of data requiring an unacceptably high level of ground support. The development and implementation of improved information management strategies which address the specific requirements of the military environment are considered to be essential. The use of advanced information management methods, such as artificial intelligence techniques, is being actively pursued by some leading HUMS researchers.

(i) Research currently being undertaken on the synthesis of loads on rotating components from loads measured in the static system, may overcome some of the major concerns relating to the practicality of measuring important structural loads in the operational environment. The synthesis technique provides significant scope to place load sensors in benign locations and to minimise the number of sensors required. Developments in this area may influence the technologies adopted for HUMS structural usage monitoring in the longer term.

(j) Very few developments have occurred in the area of structural health monitoring. Research is being undertaken on the detection of cracks in rotor blades using an analysis of airframe vibration signals. Further research into the use of redundant load sensors to provide some structural health diagnostics is being considered. When a fault (e.g. a fatigue crack) develops it is likely that the relationship between loads developed at different locations will change and redundant load sensors may be able to track such a change.

(k) The opinions of military operators vary on the desirability of maximising in-flight processing. The reduced need for ground processing and the potential to provide in-flight warnings are advantages in favour of maximising in-flight processing. On the other hand, ease of software verification and upgrade favours the maximising of ground processing.

(l) A number of experimental programs are being undertaken by military operators to test, evaluate and develop HUMS.

(m) A number of military working groups have been set up to investigate effectiveness or implementation issues for HUMS and accident data recorders.

(n) Collaborative arrangements, under The Technical Cooperation Program, in the area of effectiveness of HUMS in the military environment have been set up.

REFERENCES

1. **PA3700 Integrated Health and Usage Monitoring System**, Specification Leaflet No. GPAv 005A/6.91.

2. **Integrated Health and Usage Monitoring System (IHUMS)**, *Bristow* article, Aircraft Engineering, February 1992.

3. Reference source: Discussion between the author and Peter Gadd of NAML on 16 June 1992 at the NAML premises in Gosport.

4. **Standard Flight Incident Recorder (SFIR) Critical Design Review for the SH-60 Helicopter**, *Smiths Industries* document, 16 March 1989.

5. Reference source: Discussion between the author and Bell Helicopter Textron engineers (James D. Cronkhite, Mike Augustin, Dr Dimitri A. Dousis, Thomas E. Cooper, Herman Franks, P.E. Bina, Les Spencer, D.J. Reddy and Joe Wendelsdorf) at Fort Worth on 27 May 1992.

6. Reference source: Discussion between the author and US Army AATD SAVRT-TY-ASR (Reliability, Maintainability and Mission Technology Division) representatives (Gene A. Birocco, Jack Tansey, Ming-Leung Lau and Harvey R. Young) at Ft Eustis on 8 June 1992.

7. **Flight Data Recorder / Cockpit Voice Recorder and Health and Usage Monitoring Systems**, *Teledyne,* Document TCD3451A, January 1991.

8. J.E. Land and G. Daniels, **Helicopter Flight Data Recorder / Health and Usage Monitoring System**, *Teledyne* Document TCD3469, presented at the 16th International Symposium "Aircraft Integrated Monitoring Systems (AIMS)", September 1991, Munich.

9. **FDR / CVR / HUMS System Specification**, *Teledyne* company specification document (author's copy not dated or given a document identification number).

10. Rotorcraft Report Brief, *Rotor & Wing*, May 1993.

11. **SHL Gas Path Monitoring Technology EDMS & IDMS**, *Stewart Hughes Limited* brochure G345(1), copyright 1990.

12. F. Colucci, **Particle Prognosis**, Defence Helicopter, Vol. 12, No. 3 June - July 1993, *Shepherd Press* Publication.

13. K. Daly, **Sikorsky to offer S-76 HUMS**, *Flight International*, 11 - 17 August 1993.

14. Reference source: Discussion between the author and Richard A. Sewersky (Project Engineer, Advanced Research and Development) of Sikorsky Aircraft Division on 2 June 1992 at the Stratford premises.

15. Reference source: Discussion between the author and Stephen L. James (Rotorcraft Transmissions Surveyor, Safety Regulation Group) of the CAA on 11 June 1992 at the CAA premises in Gatwick.

16. Reference source: Discussion between the author and Dr Mike Andrew (Managing Director Engineering Diagnostic Systems) of MJA Dynamics on 16 June 1992 at the Southampton premises.

17. Reference source: Discussion between the author and GEC-Plessey representatives (Don Frew, Dennis L. Cooke, Ted Stickley and Roger Knock) at Portsmouth on 18 June 1992.

18. Reference source: Discussion between the author and Kenneth Pipe of SHL on 17 June 1992 at the Eastleigh premises.

19. M. Andrew and H. Azzam, **The Application of Math Dynamic Models to Characterise a Range of Helicopter Rotor System Faults**, Paper No. 91-22 presented at the Seventeenth European Rotorcraft Forum, September 1991, Berlin, Germany.

20. Reference source: Discussion between the author and C. Samuel Ventres of TII on 1 June 1992 at the TII premises in Bedford, Massachusetts.

21. H. Azzam and M. Andrew, **The Use of Math-Dynamic Models to Aid Development of Integrated Health and Usage Monitoring Systems**, *MJA Dynamics,* Reference L07/c428-079.

22. Reference source: Discussion between the author and Clifford T. Gunsallus of Kaman Aerospace Corporation on 3 June 1992 at the Kaman premises in Bloomfield, Connecticut.

23. Reference source: Discussion between the author and Jim Nurse of MOD-PE on 12 June 1992.

24. **Usage Monitoring Working Group (UMWG) Report to the HHMAG**, January 1994.

25. C.T. Gunsallus, W.L. Pellum and W.G. Flannelly, **Holometrics: An Information Transformation Methodology**, *American Helicopter Society,* 44th Annual Forum, June 1988, Washington, DC.

26. C.T. Gunsallus, **Rotating System Load Monitoring Using Minimum Fixed System Instrumentation**, *American Helicopter Society,* National Specialists Meeting on Fatigue Methodology, October 1989, Scottsdale, Arizona.

27. **Flight Loads Recording System for Helicopters**, Information leaflet on the ESPRIT/Kaman Model KE-6100 flight loads monitoring system.

28. Reference source: WHL letter to AMRL (from Tony Duthie to author) Ref. MKG/ACD/BEL/P.3628 of 1 February 1993, and discussions between the author and Duthie when he visited AMRL on 12 November 1992 and on 11 March 1993.

29. M. Andrew, **Recent Developments in Airworthiness Assurance Using Unsupervised Diagnostic Systems for Helicopter Maintenance**, Paper II.7.1 presented at the Sixteenth European Rotorcraft Forum, 1990.

30. **Diagnostic System Technology**, *Civil Aviation Authority*, MJA Dynamics presentation to the 15th Meeting of the Helicopter Health Monitoring Advisory Group (HHMAG), November 1991, Aviation House, Gatwick.

31. Reference source: Discussion between the author and NAWC engineers (Daniel P. Archer, William C. Emmerling and Jim Carney) on 4 June 1992 at Trenton.

32. **Hive of Industry**, *Flight International*, 29 September - 5 October 1993.

ANNEX A

TTCP HTP-7 COLLABORATIVE STUDY ASSIGNMENT

TTCP HTP-7: **Propulsive and Mechanical Systems Condition Monitoring and Diagnostics**

Technical Area: **KTA2:** **Mechanical Power Train Monitoring**

Study Assignment: **Effectiveness of Helicopter Health and Usage Monitoring Systems (HUMS) in the Military Environment**

1. Background

There is a significant thrust within the helicopter community to introduce integrated (multi-function) HUMS to enhance airworthiness monitoring and to provide maintenance cost benefits. HUMS are now coming into service into some classes of civil helicopter as part of overall systems which include a mandatory crash data recorder (CDR). Military operators are not bound by the mandatory CDR requirement and may need to assess their requirements somewhat differently to civil operators. Most military operators are deeply involved in this task with various working groups and programs being set up to help to assess requirements.

HUMS functions of primary concern for this collaborative activity are those for the dynamic system (defined here to comprise engines, transmission system, rotor system and load bearing elements of the flight control system). A specialist group working in the helicopter structural loads and usage monitoring areas is included within HTP-8 "Structures and Dynamics of Aeronautical Vehicles" and in particular in the Collaborative Study Area M "Helicopter Structural Usage Monitoring". Close cooperation with this Study Area in the assessment of usage monitoring requirements is essential.

2. Study Assignment Proposal

Provision of documentation by participants is proposed in the area of HUMS effectiveness assessment, and associated plans/programs. To a large extent relevant work is already in progress in participating countries. Australia (K.F. Fraser) would provide a coordinated document based on member inputs.

The scope of this activity should ideally be broad enough to cover the overall functional requirement for HUMS airborne recording and ground station analysis. For most military operators the level of cost benefits represents a major factor in deciding the way ahead and any information to throw light on this difficult topic would be of great value.

3. Objectives

The objectives are to:

(a) Examine and prioritise HUMS functional requirements for military helicopters.

(b) Assist participants to establish whether fitting HUMS would be worthwhile.

4. Assessment Method

Various issues which military operators are currently grappling with in respect of helicopter HUMS would be examined. Coordinated documentation would be provided to assist participants to assess their particular requirements. Some of the major issues which would be examined are listed below:

(a) Is the HUMS requirement to be considered alone or as an add-on to crash data recording (cockpit voice recording CVR and/or flight data recording FDR)?

(b) What are the health monitoring requirements and their priority in terms of both airworthiness and cost benefits?

(c) What are the usage monitoring requirements (including whether there is a case to extend capability to track lives of engine and other dynamic components according to actual severity of use)?

(d) What is the perceived status of technologies to meet functional requirements?

(e) Can HUMS evolve after being put in service?

(f) Is there a case for providing any in-flight warnings?

(g) Is there a case for performing much of the required data analysis during flight?

(h) What are the requirements for data analysis and presentation, including elapsed time within which the results of various levels of analysis must be available?

(i) Can the large quantity of information be properly managed?

(j) Is the monitoring system more reliable than the mechanical system it is monitoring?

(k) How generic/aircraft-specific are the HUM requirements?

(l) To what extent does retrofitting limit the functions which can be provided in a HUMS?

(m) What direct maintenance cost benefit (or penalty) would accrue from fitting HUMS to a fleet?

(n) Can a notional cost benefit figure be attributed to airworthiness type monitoring to prevent the "one in a million" accident with HUMS?

(o) Are the systems which are commercially available at this time adequate to meet requirements?

(p) In what areas should the main thrust of future R & D be focussed to improve benefits attainable from the use of HUMS.

5. Input Data

Most participants are undertaking work which is directly relevant to this assignment. Some possible sources of input are listed below.

US Army

- Army Aviation Maintainability Strategy Study Group (AATD Ft Eustis) looking at health and usage monitoring requirements - terms of reference, reports etc.
- Proposed FDR trial fitment to MH-60 - program details and results.

US Navy

- SH-60B propulsion and drive train collaborative program - findings.
- FDR fitted to SH-60B helicopters - program details.
- Structural Data Recording Set (SDRS) for all Navy helicopters - program details.

UK

- Tri-Service Helicopter Health Monitoring Implementation Working Group (HHUMIG) - terms of reference, reports etc.
- RN proposal to trial fit a Bristow IHUMS to a Sea King helicopter - program details and findings.
- MOD(PE) investigation of "Specification for Project Definition Study of Health Usage Monitoring for Helicopters" - results of study when available.
- EH101 Health and Usage Monitoring (HUM) working group - reports etc.

Canada

- Planned fitting by the DND of a partial Teledyne/Stewart Hughes CVR/FDR/IHUMS to the 100 Bell 412 light utility helicopters which are to be purchased (the DND proposes to implement further health and usage capabilities within this system in the future) - progress reports.

Australia

- Strategic Planning for Helicopter Crash Data Recording and Maintenance Monitoring in Australia Working Party (all services) - reports.

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7. Reporting

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8. Conclusions

Final Study Assignment report to be issued by April/May 1995.

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An Overview of Health and Usage Monitoring Systems (HUMS) for Military Helicopters

K.F. Fraser

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16. *ABSTRACT*

The application of HUMS for military helicopters is lagging that for civil helicopters, but military operators are seriously examining the effectiveness of such systems for their fleets. The material presented in this document is based mainly on the author's recent discussions with researchers, manufacturers and military operators. It outlines some of the important issues which operators face and some initiatives in the area.

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